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XR for Transformable and Interactive Design

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Abstract

This article aims to show the applicability and evaluation of a teaching-learning method based on user experience (UX) design and extended reality (XR) in architectural studios. In the summer of 2023, the XR Assisted: Transformable and Interactive Design studio utilized the UX+XR teaching-learning method. During the studio, the emphasis was on designing a transformable and interactive architectural installation, with the UX as a center and XR, artificial intelligence, and inmotics as design and visualization tools. In the UX+XR method, the users were the students, and each student designed transformable architecture by applying UX strategies to their specific urban installation users. The UX+XR method had four phases. Each phase incorporated a cross-strategy UX+XR during the design process stages. Using UX+XR, the participants designed an architectural installation where the concepts of transformability, ephemerality, interactivity, flexibility, adaptability, versatility, and playfulness were present. Based on testing the six architectural installations designed during the studio using the UX+XR method, our data showed that XR enhanced the designer's perception, constituted a new means of expression on an accurate scale, and is a highly immersive and interactive resource for communicating ideas and reinforcing visualization, simulation, stimulation, and interaction. XR is a powerful tool that, as used in the designed method, allows an elevated level of visual communication, understanding of spatial dimensions, and an effective multi-user collaborative strategy for evaluating the designed proposals.

Keywords

artificial intelligence; extended reality; inmotics; interactive architecture; transformable architecture; user experience

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1. Introduction

This research evaluates a teaching-learning environment that implements user experience (UX) design and extended reality (XR) for transformable and interactive architecture within an XR-assisted studio at the School of Architecture and Urban Planning at the University of Wisconsin – Milwaukee (SARUP-UWM).

We developed a comprehensive method that combined UX with XR, including artificial intelligence (AI) and inmotics as technological resources for automation and interaction. This method consisted of four phases, integrating UX and XR strategies to improve the architectural design process.

This study proposes a fusion of AI and XR to establish a typology of interactive design for user-responsive installations. Consequently, it challenges researchers and designers to leverage digital technology in crafting immersive and meaningful experiences.

The XR Assisted: Transformable and Interactive Design studio was a 6-unit credit workspace that enabled participants to design by implementing the UX+XR method as a supported strategy to enhance perception, visualization, simulation, and collaboration during the design process. This studio focused on improving UX in architectural spaces, emphasizing inclusion and accessibility. The students were required to design a transformable architectural product that responds anatomically and functionally to the diversity of movements and anthropomorphic measurements of the user and generates a sensory-emotional system that stimulates the creation of intimate and collective memories.

XR improves our perception of the tectonic environment through synthetic environments. Various innovative technologies have transformed practices over time in the architecture, engineering, and construction industry. These advancements include hand-drawn drawings, physical models, computer graphics, multi-dimensional digital models, and building information models. Recently, the rapid development of extended reality (XR) technology has further revolutionized the architecture, engineering, and construction industry. XR has the characteristics required for solving distance, space, and time constraints that we cannot complete with traditional design strategies (Chi et al., 2022). Assisted with external devices, XR permits the experience and stimulation of the senses through the digital recreation of scenarios and establishing a remote and synchronous collaborative design environment (De La O Miranda & Cortés Campos, 2023).

When working with XR, it is essential to incorporate UX strategies. Key verbs for success include travel, discover, perceive, interact, navigate, and feel. These verbs are crucial for an efficient UX predesign in digital and physical experiences.

The UX+XR strategy allows the designer to recreate what the potential user can feel and assess the design's spatial qualities on an accurate scale. Through XR, it is possible to superimpose the digital design in the physical context using augmented reality (AR) or mixed reality (MR). This allows us to identify environmental relationships, proportions, and functionality. When implementing UX strategies in the architectural process, the user studies the anatomy and spatiality of their contextual elements, both individual and collective.

The benefits of AR and virtual reality (VR) in education are increasingly becoming evident across various fields. In 2019, 436 AR/VR education studies were submitted to the Web of Science (Garzón, 2021). These studies have reported several advantages for students, which include improved information retention, enhanced visualization abilities, increased attention and motivation, improved outcomes and success rates, facilitated access to a psychological "flow" state, and collaborative benefits (Pinter & Siddiqui, 2024). Interactive 3D models allow students to manipulate and explore complex concepts hands-on. AR and VR technologies can transform education by offering interactive and immersive learning environments that boost student/teacher skills, understanding, and knowledge retention (Allcoat et al., 2021; Anwar et al., 2023).

2. Fundamentals to UX, User-Centered Design, and XR as Formal Evaluation Method in Teaching-Learning Environments

2.1. UX Essentials: User-Centered Design, Accessibility, and Usability

"User experience" was coined in the 1990s by Don Norman, co-founder of Nielsen Norman Group, a leading consultancy in UX design. It encompasses all aspects of user interaction with an ecosystem, environment, device, or service. The UX method emphasizes user involvement before, during, and after design. It has a qualitative focus and aligns with the agile "design thinking" process (Aguirre-Villalobos et al., 2023; Garrett, 2011). The UX method implies the following stages:

- Empathize: Understand users and investigate their pains, hopes, and habits in relation to the ecosystem in which they operate;
- Define: Research users and synthesize solutions to propose answers;
- Ideate: Generate project ideas based on user research;
- Prototyping: Generate high, medium, and low fidelity models to obtain user feedback;
- Testing: Evaluate how users perceive both physical and digital models and measure their effectiveness.

The process is a non-linear iterative model. With each change, users can generate opportunities in the maturity of the project or services (Mootee, 2013; Osterwalder et al., 2013).

The UX method focuses on understanding user interaction with products or services and enhancing their functionality and user satisfaction. It is systematic, participatory, and iterative, involving the user in all research and final development stages. Based on user-centered design, UX considers accessibility and usability central aspects (Aguirre-Villalobos et al., 2024; Gallagher & Getto, 2023).

User-centered design is a discipline that prioritizes users' needs and experiences in the design process. In the context of digital technology such as XR, AI, and inmotics, user-centered design ensures that these technologies are accessible, intuitive, and satisfying for users. It guides the design and implementation of digital solutions and ensures that the product of design seamlessly integrates into users' daily lives through research, testing, and continuous improvement (Aguirre-Villalobos et al., 2021, 2023).

2.2. XR as a Teaching-Learning Environment

The following section presents fundamental concepts and perspectives about integrating XR tools in education, focusing on architectural studies and complementary technologies such as inmotics (automation) and AI. These tools facilitate immersive learning, support the creation of transformable architectural spaces, and optimize data-driven learning. Furthermore, we identified several XR applications designed to create dynamic environments that respond to users' needs. This exploration considered a range of academic approaches and perspectives regarding their deployment.

XR implies different digital realities, with "X" as a placeholder for any form or new reality. This concept encompasses using XR as an abbreviation for xReality (Rauschnabel et al., 2022). XR is the frame that includes multiple types of new digital realities, like VR, AR, MR, virtual 360-degree tours, and immersive technologies tools, to simulate and enhance the perception in synthetic environments, where the "X" implies the unknown variable. In "xReality," thus, "X" indicates "all" new reality formats (Rauschnabel et al., 2022).

XR in learning processes has a valuable positive impact on the learners. It democratizes experiential learning, creates an overlay of data and knowledge, and increases student productivity. VR-based education involves wearing a headset or using other devices to experience a simulated 3D environment with which users can interact. Immersive learning involves a broader range of technologies, including VR, AR, MR, and other interactive environments (Abd El-Latif et al., 2023).

To define MR, we adopted the concept proposed by Rauschnabel et al. (2022), who present a continuum where MR is between AR and VR, with the natural world and VR at opposite ends. Unlike Milgram et al. (1995), they do not conceptualize MR as a general term but as a specific reality that "combines the real with the possible" (Farshid et al., 2018). Similarly, Flavián et al. (2019) describe "pure mixed reality" as a technology between augmented reality and augmented virtuality (Ortega Rodríguez, 2022; Panko, 2023).

VR encompasses diverse, immersive learning environments that administrate educational content, enhance comprehension, and establish secure virtual laboratories within various educational domains, including healthcare, engineering, science, and general education. Educational materials, particularly those related to the anatomical structure and functions of human organs or the cosmos, are challenging to grasp through textual means alone. VR technologies can facilitate comprehension and offer sustained opportunities for practice and experiential learning (Anwar et al., 2023; Petit et al., 2022).

VR solutions are effective in various educational settings and are well-received by students (Anwar et al., 2020; Huang et al., 2010; Kiss, 2012; Panteldis, 2009). VR implementations typically require user input or interaction, which promotes active engagement over passive learning approaches. The concept of virtual reality learning environments (VRLEs) revolves around providing students with immersive 3D environments with which they can interact. Although existing studies have shown positive student perceptions of VR in education, they emphasize the importance of incorporating a solid pedagogical foundation in any meaningful educational innovation (Huang et al., 2010). Over the past few years, VR has gained significant attention for its potential to revolutionize education. A growing body of research examines the use of VR in improving students' cognitive skills in various educational contexts, including science, technology, and engineering (Anwar et al., 2023). AR and VR represent potent tools for accessing and assimilating precise information when it is most opportune. AR and VR enhance learning by simulating real-life experiences that evoke emotions or allow users to experience someone else's story. These technologies are highly valuable for a wide range of users and sectors (Chu & Ko, 2021; Ramos Aguiar & Alvarez Rodriguez, 2024; L. Wang, 2022; Z. Wang et al., 2024).

2.3. XR Applied to Education in Architectural Studies

In educational usage of XR, especially for architectural studios, the UX experience must be considered a parameter to facilitate the project process and effectively design based on user needs. When interacting with a designed space or urban context, UX results from a person's perception of that designed space, or context. UX can be used by a collective defined by human and non-human relationships involving the natural or urban ecosystem and has a participatory and inclusion objective (Aguirre-Villalobos et al., 2021).

The designer—in this instance, the student—should be able to effectively observe and interpret, as delineated by the stages of UX Empathize and Define. The designer must understand the users' challenges and expectations to integrate the contextual circumstances that address the collective user needs. This process involves collaboration with other designers within the group to establish operational systems (Ferrer-Mavárez et al., 2020).

2.4. Incorporating AI and XR to Enhance Data-Driven Learning

With XR, AI can enrich how machines learn from data without heavy programming, leverage statistical learning techniques to predict attributes, and attain progressive learning capabilities that accommodate and analyze new data. AI can bridge the gap between simulation and reality. With AI strategies, developers can create high-quality holographic images that look good on LCD screens (Gergana, 2022). The potential of incorporating AI and XR as part of space systems promises a more efficient performance, especially useful for creating responsive urban installations and learning spaces for users with specific characteristics (Marín-Morales et al., 2018; Mehta & Singh, 2024).

XR utilizes computer-generated virtual environments to enhance human capabilities and experiences, facilitating more effective learning and discovery skills. On the other hand, AI attempts to replicate how humans understand and process information (Loshin, 2013; Rauschnabel et al., 2022; Romero Morales et al., 2010) and, combined with a computer's capabilities, process vast amounts of data without flaws.

In the United States, after the oil crisis of the 1970s, the primary objective of generating savings in consumption was to avoid expenditure (Romero Morales et al., 2010). After the first automation, air conditioning and intruder control systems, i.e., alarm systems, were developed. The discipline of researching and developing this technology was called "home automation."

Home automation—in this article, "domotics"—has a genesis analogous to "informatics," replacing the prefix that means information with another derived from the Latin word "domus," which means house. The root of the word "domotics" is the sum of "domus" and "tics." The term "domotique" (from French) is noteworthy for its association with robotics (Domotique, n.d.). In this way, home automation or "domotics" is robotics applied to construction. When addressing non-residential tertiary structures, "building automation" becomes pertinent. This discipline is primarily concerned with energy management, encompassing the automation of tasks and operations (Chi et al., 2022; Romero Morales et al., 2010).

This research proposes AI, building automation, and XR technology to generate interactive architecture where the space contains elements responsive to users' needs. For this article, inmotics is defined as a building automation system: "An inmotic system is a network that controls, supervises, and optimizes devices and agents in charge of managing different building areas; thus, each component performs its function automatically without leaving the centralized control" (Strauch-Gómez et al., 2017). The potential of incorporating inmotics, AI, and XR into space systems would be beneficial for creating transformable architecture for users with specific characteristics (Calderón Zambrano et al., 2023).

2.5. Towards Transformable Architecture Through the Integration of an Adaptive System

In this research, transformable architecture is defined as incorporating a responsive system that enables the modification of the envelope or components within an architectural space according to the users' needs. Transformable architecture can create an innovative and dynamic space in which users have more opportunities to change their surrounding environment effectively. It also opens a way to meet environmental needs and respond to unexpected situations (Asefi, 2012). When discussing transformability, two or more features or systems work together to produce a specific change in the architectural space grounded on transformation principles. The principles of transformation encapsulate the physical and perceptual reconfiguration of internal spatial layouts and membranes (Andjelkovic, 2016). This is accomplished by manipulating design elements, involving opening and closing, expanding and contracting, joining and dividing, and pulling in and drawing out. The alteration of disposition, shape, or structure leads to the desired transformation. This process is primarily accomplished through the rotation, translation, and combinations of rotation and translation of primary or complex (spatial) geometric elements.

The symbiosis of transformability and technologies within the multiple dimensions of contemporary design generates a technological system, a design strategy, and a defined typology of digital technology and architectural tectonics—a form of living architecture as the envelope or second skin between the human and its habitable context. The design of each skin is as unique as its users and implies infinite solutions for specific users. In addition, this methodology and typology of architectural spaces could respond to multiple programs: interior design, urban and public spaces, educational, temporary architecture, medical, residential, commercial, recreational, historical, and tourism. This symbiosis was one of the leading design objectives during the XR Assisted studio at SARUP-UWM.

2.6. Evaluation: Framework and Essential Aspects for Evaluating a Teaching-Learning Environment Implementing

UX+XR It was crucial to consider both the UX and the learning outcomes to evaluate a teaching-learning environment that integrates UX and XR. According to Kim et al. (2020), a systematic review of VR systems highlights the importance of usability, immersion, and user satisfaction, which directly influence the effectiveness of XR environments for learning. Usability also involves emotions and how the user creates and develops the experiences. Effective computing can improve interaction in XR, helping to adapt the experience to the user's feelings and needs and increasing its effectiveness in educational contexts (Ferrer-Mavárez et al., 2023; Guo et al., 2020).

In his work, *The Design of Everyday Things*, Norman (2013) highlighted the importance of usability and UX in designing digital interactions. In addition, Aguirre-Villalobos et al. (2024) propose that effective learning comes from direct interaction in the design process of the usable environment and the value of implementing tools that align with the use of XR for teaching. Regarding implementing XR technologies in education, Jacobsen et al. (2022) show that the experience in virtual environments can be as practical as in physical environments, highlighting the validity of using XR in teaching. These studies agree that evaluating the UX in XR should focus on personalization and intuitive interaction effectiveness to facilitate collaborative learning. In evaluating immersive experiences in VR environments, they emphasize the importance of usability, immersion, and feedback in creating effective learning strategies (Beqiri, 2016; Jacobsen et al., 2022).

It was crucial to consider the critical aspects related to the user in the context of the xReality-assisted design process. This approach was essential for evaluating the effectiveness of employing UX combined with XR in the instruction of architectural design. The key aspects are delineated as follows:

- Usability: How users interact with the virtual architectural environment, ensuring that navigation is intuitive and efficient;
- Interaction and immersion: The ability of users to interact with human-scale virtual space at a prominent level of realism and whether the environment generates an adequate sense of presence and immersion;
- Accessibility: Ensure the design is inclusive and accessible to users with different navigation and interaction abilities;
- Sensory feedback: Evaluating the appropriate use of visual, auditory, and haptic stimuli to improve the understanding and experience of space;
- User satisfaction: Assessing users' holistic satisfaction regarding comfort, aesthetic appeal, and functionality within the architectural context;
- Learning effectiveness: How the XR environment facilitates spatial understanding and the assimilation of complex architectural concepts.

When evaluating a teaching-learning environment that combines UX and XR, it is essential to consider:

- User engagement: Evaluate the level of attention, interest, and motivation that the XR learning environment generates in students;
- Knowledge retention and transfer: Measure the effectiveness of the experience in assimilating and applying complex concepts in architectural design;
- Feedback and personalization: The system's efficiency in adapting the content and providing feedback in real-time to improve learning;
- Efficiency and fluidity of interaction: The tools and functionalities enable an efficient and seamless UX during the teaching process;
- Learning outcomes assessment: Assess the alignment between pedagogical objectives and their achievement through the XR platforms, measuring technical and comprehensive skills;
- Technological adaptability: The degree to which the XR environment adapts to different devices and technologies without compromising the UX.

3. Method

Our project focused on integrating XR and UX stages to improve the architectural design process and optimize teaching-learning environments centered on users' and designers' needs. To achieve this integration, we identified the layering stages among the phases of the UX design process, the architectural design process, and the XR tools as facilitators in the spatial design process (Figure 1).

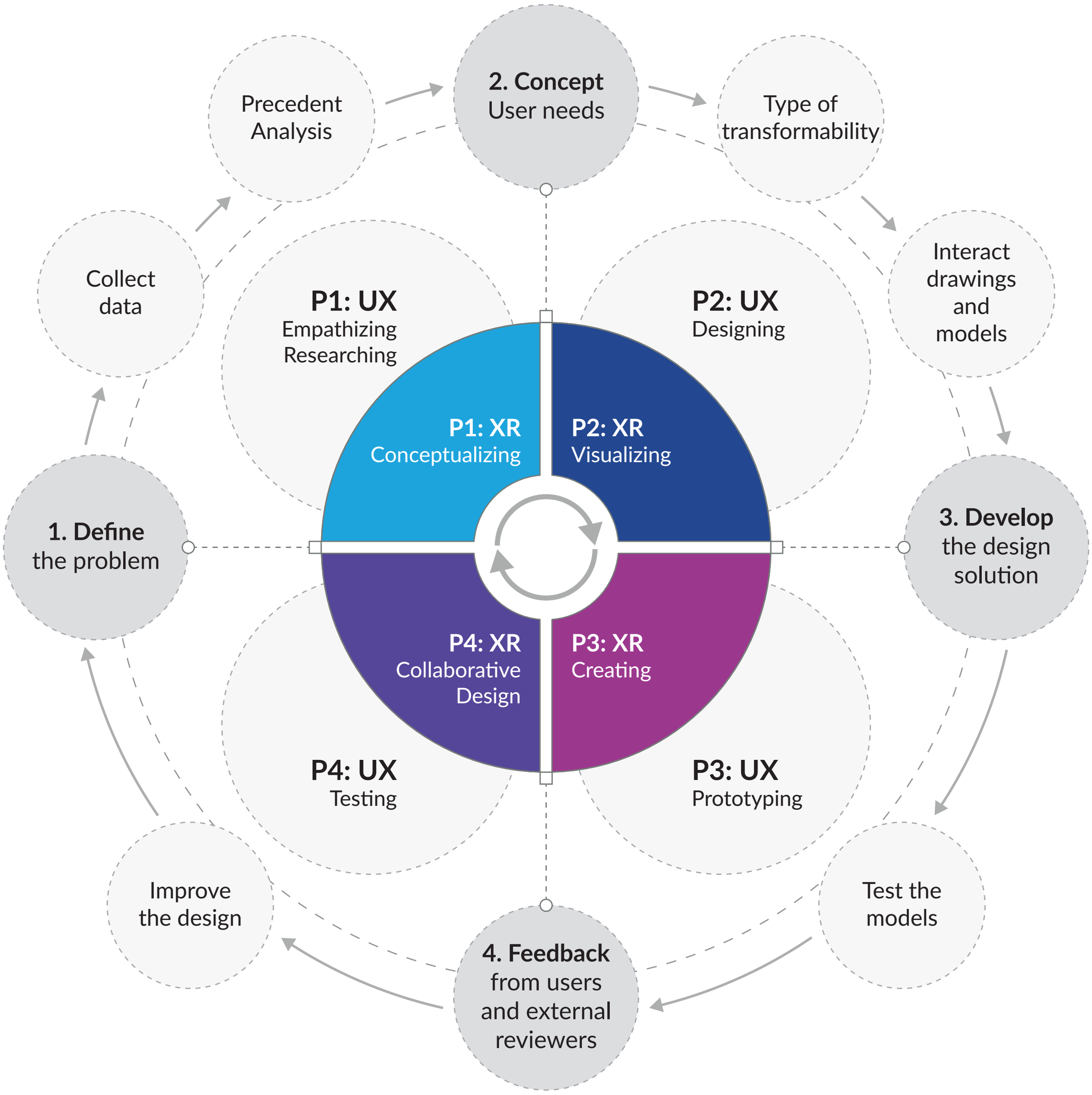

Figure 1. UX+XR method in architecture design studios.

To develop the UX+XR method, we formed a transdisciplinary team of UX, XR, transformable architecture design, and inmotics experts to lead an intensive summer architecture studio with juniors, seniors, and graduate students to apply and assess the UX principles implementing XR during the design process. Due to the complexity of the design problem and the process involved in using XR, it was necessary to allow upper-level students to participate in the student range.

3.1. Participants

This research was part of a collaborative project involving three universities from different countries: the United States, Chile, and Argentina. This project was led by an international team composed of an academic researcher and an IT assistant from SARUP-UWM in collaboration with a UX expert consultant from the Escuela de Arquitectura de la Universidad Tecnológica Metropolitana in Chile, and a building automation expert from the University of Cordoba in Argentina.

We established a methodological model based on UX design and using XR. This approach focuses on comprehensive qualitative data analysis to develop an academic proposal (Martinelli et al., 2024). The research was conducted in the context of a 90-hour workshop in the architecture program at SARUP-UWM. This workshop serves as the setting, data source, and academic framework for the methodological implementation during the design process.

During the first studio phase, the students had to identify social issues in Milwaukee and devise adaptable design solutions utilizing UX+XR, inmotics, and AI technologies. This qualitative, inductive approach focused on understanding phenomena through collecting and analyzing unstructured data. Techniques include participant observation, semi-structured interviews with students during UX+XR methodology implementation (Aguirre-Villalobos et al., 2024), the use of observation notebooks in student projects (González et al., 2023; Montes Sosa & Castillo-Sanguino, 2024) and following UX+XR methodology stages to assess the applicability of the teaching-learning process by the lead course instructor (Rodrigues de Andrade, 2023).

3.1.1. Population and Data

Data consisted of semi-structured qualitative interviews conducted between June and July 2023 with young students aged 22 to 25, all enrolled in the architecture program at SARUP-UWM in the XR Assisted studio. Of the 11 interviewees, five identified as female and seven as male.

3.2. Design

Throughout the research process, students applied UX+XR for transformable and interactive design in architecture, creating diverse projects such as urban mental health stations, interactive parks, housing for the homeless, climate-adaptive bus stations, urban educational spaces for children, and public baby feeding spaces.

The strategy to design transformable architecture within the UX+XR method implied the following steps: (a) identify the type of transformability that responds to the need or problem; (b) identify the elements of design that need to be transformed (skeleton, skin, shell fragments, etc.); (c) identify the type of materials and mechanisms that allow the desired transformation; (d) determine the transformation principles; (e) define the joins and articulators for transformability; (f) determine feasibility and human scale that activates and controls transformability; and (g) determine the inmotic and digital elements that trigger transformability and technical aspects.

By crossing UX+XR with AI and inmotics in architectural design, we achieved efficient solutions with diverse aesthetics and innovation focused on technology-assisted humans with interactive options to increase their quality of life. In this context, the XR Assisted studio aimed to involve students in cross-design processes that solved urgent societal problems in conjunction with the emerging digital design technologies overlapping

UX+XR+AI. This studio's approach showed the phases of UX and XR at specific moments in the design process, addressing multiple technological platforms for the virtual simulation of products. Students used their cell phones, computers, HTC VIVE, Oculus Quest 2, or Meta Quest 3 in the XR studio room during all the phases.

3.3. Procedures

The definition of the proposed methodological model phases resulted from overlapping the main stages of the architectural design process, the UX methodology, and the XR strategies proposed in architecture (Figure 1).

The studio was designed in four phases. The program consisted of two weekly classes, each lasting two weeks (see Figure 2). The first phase was UX Empathizing and Researching and XR Conceptualizing. In the first phase, the students clarified the users' problems and needs in the project's context. The students applied problem analysis, empathy mapping, and exhaustive research, including interviews and proto-persona creation.

Students created spatial and formal conceptualization design proposals using Tilt Brush, Gravity Sketch, and Twigital AR applications. Understanding the human scale was one of the most relevant advantages of using AR. This resource permitted us to explore the initial concept of design and create conceptual physical models into digital models by scanning the models and visualizing them using Twigital. Those apps allowed an interactive re-creation of architectural concepts, such as expandable space, flexibility, transformation, ephemerality, elasticity of space, and metamorphosis. This phase defined the user characteristics, context, program, and initial speculations about interactivity and transformability.

In the second phase, UX Designing with XR Visualizing, the students used mood boards, style guides, sketches, or visual models to introduce the user to the design image closest to the result. Next, the students used Enscape, Twinmotion, and Kuula to visualize the design in an elevated level of detail. In this phase, students defined the architectural components, materials, and diagrams for the AI or inmotics aspect. Students identified the strategy for transforming the design and representing the flexible space to define the interactive element in the installation and constructive process.

In the third phase, UX Prototyping and XR Creating, diverse prototypes were presented to users at various levels of fidelity, ranging from low to high, to receive their review and feedback on each at distinct stages of development. Prototype details were iterated in collaboration with users, refining them to ensure they felt comfortable and could be interacted with effectively. This phase focused on creating a physical prototype by building a model at 3/4" = 1'0" scale, using defined materials, and modeling structural joins at 1 1/2" = 1'0" scale. Students placed the ephemeral design on-site using AR. They created simulations and reviews during this phase, implementing Enscape, Twinmotion, and Twigital. Students also created a detailed construction manual.

In the fourth phase, UX Testing and XR Collaboration, the students evaluated the final prototype using collaborative testing techniques. Extensive testing identified issues or areas for improvement. Based on user feedback, design details were refined to ensure an optimal and satisfying experience. We evaluated the proposals in collaborative design environments using Arkio with external reviewers. Arkio served as a multi-user virtual and interactive platform for reviews. Students generated a collaborative virtual environment that could be experienced in real-time.

Figure 2. Example of design production per phase in the UX+XR method for transformable architecture.

3.4. Measures

Two evaluation stages developed from various data collection techniques were applied to progressively develop conjectural ideas (Hernández-Sampieri & Mendoza, 2018). We obtained our data from projects on transformable architecture using notebooks. Furthermore, we conducted interviews to assess the process's importance in student learning and comprehensive knowledge acquisition to evaluate the effectiveness of applying the UX+XR methodology in the project design phases (Buenaño et al., 2023).

This study utilized semi-structured interviews to evaluate the design process from students' perspectives. Architectural design requires meticulous process documentation, achieved through observation and the systematic recording of notes or feedback during studio sessions. Central to the architecture design process is decision-making aimed at resolving design problems that may have more than one possible solution, a task that can often be subjective. For this research purpose, documentation of this process was essential, requiring observation and detailed notes to be recorded in notebooks. The observation focused on the students' curiosity, the quality of their interactions, and the evolution of their ideas, with a particular emphasis on using UX+XR platforms. These platforms were used to visualize, communicate, simulate, and interact with architecture that can be transformed.

We designed and applied semi-structured interviews for the students to assess the UX+XR structure and flexibility. They allowed the exploration of previously defined topics while opening spaces for interviewees to delve deeper into unforeseen aspects. This technique is precious for capturing students' complex and subjective experiences in learning UX and XR, where interactions and emotions can influence their process of understanding and where students' subjective interactions and perceptions play a fundamental role in the learning process.

The observation notebook was vital in the XR Assisted: Transformable and Interactive Design project. It documented the findings, reflections, and adjustments during its development and detailed the creative and technical process. Evaluation measures included the coherence and comprehensiveness of the content, the reflective capacity, the applicability of ideas, the innovation shown, and the evolution of the project over time.

We implemented a notebook to facilitate the measurement of various aspects observed in the quality of the student projects. These include (a) concept, (b) design quality, (c) functionality, (d) transformability and spatial qualities of the design, (e) visualization strategies (XR), and (f) interaction and collaboration during the design process with XR (see Table 1). This approach allowed for a comprehensive assessment of the final design product using the UX+XR methodology. This evaluation process benefited the professors and the students, encouraging self-assessment and peer assessment, thus promoting a collaborative work approach among the students.

A rubric was applied in which the project's functionality and creativity were measured and evaluated through the distinct stages of the UX process: research, design, prototyping, testing, and feedback. The rubric focused on how each phase responded to the UX, ensuring the development focused on usability, interaction, and end-user satisfaction at each design stage. The rubric criteria for assessing the final design included concept, design quality, functionality, transformability and spatial qualities of the design, visualization strategies (XR), and interaction and collaboration during the design process with XR.

Table 1. Management and systematization of notebooks.

Observed Traits	Evaluation Type	Achievement Level Scale (%)				
		Very Deficient	Deficient	Sufficient	Excellent	Outstanding
(a) Concept Creative characteristics, innovation	SA PA	0 1	0 1	1 1	9 9	10 8
(b) Design Quality Coherence between concept, narrative, and final design product	SA PA	0 0	0 0	0 1	2 4	18 15
(c) Functionality It is usable, adaptable, and responds to the public and the market's needs	SA PA	0 1	0 0	0 1	3 2	17 16
(d) Transformability and Spatial Qualities of the Design Applied technology in design/structural design/spatial relationships	SA PA	0 0	0 0	0 3	5 5	15 12
(e) Visualization Strategies (XR)	SA PA	0 0	0 0	0 0	3 5	17 15
(f) Interaction and Collaboration during the Design Process with XR	SA PA	0 0	0 0	1 1	2 4	17 15

Notes: The Evaluation Type values were SA = self-assessment, PA = peer assessment; the Achievement Level Scale value ranges are Very Deficient = 19–0, Deficient = 39–20, Sufficient = 59–40, Excellent = 79–60, and Outstanding = 100–80.

4. Results

4.1. Analysis of Project Results and Design Process with UX and XR by Observed Traits

Data indicated that self-assessment and peer assessment primarily categorized the creative and innovation aspects as Excellent (9) and Outstanding (10). They were notable for the consistency between their creative traits and the innovation in their concepts. The results strongly emphasized originality, aligning self-assessment and external evaluators' perceptions. They suggest a solid understanding of user-centered design and an ability to communicate the concept effectively through architectural design.

Design quality (coherence between concept, narrative, and final product) exceeded expectations. The collected data shows that the Outstanding level predominated in self-assessment (18) and peer assessment (15). The score evidenced exceptional execution in integrating the concept with the narrative. This elevated level of achievement indicated a practical ability to conduct design from initial conception to final implementation, maintaining coherence and quality throughout all process stages.

Regarding functionality, including usability and adaptation to public and market needs, the students rated self-assessment as Outstanding (17), like peer assessment, which also received Outstanding ratings (16).

This demonstrates a strong understanding of user needs and an effective ability to design practical architectural solutions adaptable to different contexts and users.

The transformability and spatial qualities of the design were another criterion for which the data exceeded expectations. In this aspect, self-assessment was mostly Outstanding (15), and peer assessment was Outstanding (12). The design's transformability and spatial qualities consistently received great evaluations, indicating careful attention to flexibility and adaptability in the built environment. These results suggest an effective response to the changing demands of users and the environment. The students were attentive to developing structural systems based on digital technologies and automation to achieve architectural transformability according to user needs, especially regarding accessibility.

The implemented XR visualization strategies were successfully applied to the students during the design process and displayed in their project presentations. The data showed that self-assessment was predominantly Outstanding (17) in the visualization trait, and peer assessment was also predominantly Outstanding (15). Advanced XR visualization strategies determined a positive perception of the project's interior and exterior space, highlighting the ability to communicate and present architectural design effectively and persuasively through innovative technologies.

Interacting and collaborating during the design process, facilitated by XR technology, was a key strategy for developing the design and gathering feedback from potential users and external reviewers. The designer and reviewers synchronized and remotely evaluated the project in one virtual space. Each actor was represented as an avatar in the virtual model, and the participants could talk, send messages, and make marks and suggestions in the review. Most students selected Outstanding (17) in self-assessment, and peer assessment was predominantly Outstanding (15) in this category. Elevated interaction and collaboration scores during the UX+XR design process indicated effective collaboration and strategic use of advanced technological tools to enhance design communication and iteration, thereby strengthening project quality and efficiency.

4.1.1. Emerging Categories Analysis

The final evaluation focused on the effectiveness of the UX+XR methodology as a strategy for transformable architecture design in the classroom. We interviewed students who participated in the studio to assess the quality and understanding of this methodology. The student interviews indicated that the UX+XR methodology enhances creative work and transformable architecture during the learning process, as implemented by professors. The interviews also identified limitations and areas for improvement to consider for future applications.

Systematizing the data allowed us to categorize the main criteria for the usefulness of the UX+XR methodology in transformable architecture design. These categories are considered fundamental criteria from both academic and practical study perspectives, addressing critical elements that structure research references for organizing information (Table 2).

Emerging categories were relevant in each stage of the UX+XR methodology for transformable architecture projects, focusing on problem definition, characterization, and stage-specific targeting. We observed the proposal's effectiveness, concepts, design quality, functionality, transformability, spatial qualities, visualization strategies (XR), interaction, and collaboration during the design process with UX+XR.

Table 2. Emerging categories in UX-XR stages.

Teaching-Learning Environment	Process Emerging Categories			
	P1 UX: Empathizing and Researching XR: Conceptualizing	P2 UX: Designing XR: Visualizing	P3 UX: Prototyping XR: Creating	P4 UX: Testing XR: Collaboration
Architecture XR Assisted: Transformable and Interactive Design	Grounding the problem. Understanding the users.	Precedents analysis. Developing: concept, narrative, and detailed design product.	Create the design: functionality, transformability, and spatial qualities of the design. Technology: visualization strategies (XR). Build design and tectonic scale models digitally in medium- and elevated-fidelity museum quality.	Effectiveness of design proposal: usability, coherence. Models' interaction and collaboration during the design process with XR. Multi-user virtual environments for collaborative design. Final presentation.

The versatility of the UX+XR methodology in academic contexts arose because it provides a structured framework that fosters creativity and effective problem-solving relevant to distinct creative areas, like industrial design, engineering, graphic design, digital design, and the arts. This approach offers valuable insights into successfully implementing a method for transformable architecture design while integrating a foundation to create a teaching-learning strategy in education.

4.1.2. Analysis of Interviews

Within the study framework, interviews were conducted with students to assess the applicability of UX+XR methodology in transformable architecture design. We organized questions around the distinct stages of the design process. This approach provided a comprehensive view of how students perceive and apply UX+XR methodology in their projects and the associated challenges and benefits. The open-ended questions posed to the students, divided by stages, are presented in Table 3.

Considering Table 3, the analysis of student interviews revealed a positive perception and significant support for the UX+XR methodology applied in transformable architecture design. Below, we present an analysis derived from responses to open-ended questions structured across the stages of the UX+XR project.

In phase 1 (P1), the interest in UX+XR showed that 75% of students were highly interested in its applicability. They described the methodology as an attractive and powerful tool that allowed for deeper understanding and implementation in their transformable architecture projects. In terms of understanding the problem based on the user needs, 75% of students comprehended the problem better by applying empathy strategies, highlighting the importance of empathizing with users. This initial understanding facilitated a user-centered approach throughout the design process.

Table 3. Open-ended questions for students regarding the applicability of UX+XR in transformable architecture design.

UX+XR Phases	Open-Ended Questions
P1. UX: Empathizing and Researching XR: Conceptualizing	1. How would you describe your interest in the applicability of UX+XR in transformable architecture projects? 2. How did you understand the problem from the empathy (definition) stage?
P2. UX: Designing XR: Visualizing	3. How did applying UX+XR in transformable architecture facilitate your understanding of the subject? 4. How did you research and analyze the needs and expectations of users in your project?
P3. UX: Prototyping XR: Creating	5. How did UX+XR support and guide you in designing solutions for the transformable architecture project? 6. Do you feel confident, with the experience gained in the course, of applying UX+XR to design solutions for transformable architecture? Why?
P4. UX: Testing XR: Collaboration	7. Do you consider that UX+XR provided a systematic pathway for your project? How does this method help you in design decision-making? 8. How did you integrate innovative ideas and user feedback in the prototyping process to create solutions? 9. Do you consider that UX+XR provided better solutions than traditional methodologies? Why? 10. How did you manage user feedback during the testing phase of UX+XR to improve and refine the prototype, ensuring that the final solution was intuitive, useful, and satisfactory for users?
About the experience	11. Do you believe UX+XR will improve your academic performance in future subjects? 12. What were the main challenges you faced when applying the UX+XR methodology, and how did you overcome them during the project development?

In P2, centered on designing and visualizing, 82% of the students affirmed that applying UX+XR facilitated identifying and characterizing the subject to create a responsive design. They noted that this methodology allowed them to approach projects more efficiently and in a more structured way. In this matter, we discovered that it was necessary to perform more interviews to learn more about the involved users. When researching and analyzing user needs and expectations, 82% of students used UX+XR tools that helped them gain valuable insights, resulting in projects more aligned with user expectations.

UX+XR provided clear support and guidance in designing solutions for 75% of students in P3. They felt supported by a methodology that allowed them to explore diverse options and select the most suitable ones for their projects. Identifying what XR tool was most efficient per phase in the design process was a takeaway for efficiency in decision-making, idea communication, and visualization.

Most students on the course, 82%, feel confident about using UX and XR in their future projects. They highlighted how this methodology improved their ability to design effective, user-centered solutions and gave them a better understanding of spatial proportions and qualities.

During P4, a systematic pathway to develop models (tectonic and virtual) was defined. The data indicated that 75% of surveyed students believed that UX+XR methodologies provide a clear framework for project development. They appreciated the structured approach and well-defined stages guiding their design process. The methodology allowed 82% of students to integrate innovative ideas and user feedback into the prototyping process. This ongoing interaction ensured that the solutions were relevant and valuable.

When implementing XR for collaborative design and comparing it with traditional methodologies, 75% of students believed that UX+XR offered better solutions than traditional methodologies. Through testing by the project team, different users, and the design team, they highlighted greater problem-solving effectiveness and improved UX. During testing, 82% of students managed user feedback to improve and refine prototypes. This practice ensured that the final solutions were intuitive, useful, and satisfactory.

Using UX and XR, strategies enriched the student's academic performance during the transformable architecture design studio by facilitating design decisions, visualization, interaction, collaboration, and testing during the teaching-learning process. According to the interviews, 82% of students expressed confidence in the potential of the UX+XR methodology to impact their academic performance in upcoming courses positively. The experience gave them valuable skills to tackle complex projects through critical thinking, collaborative work, and the methodology's systematic stage-by-stage approach.

The assessments, conducted as part of the evaluations using the UX+XR methodology, consistently revealed a prominent agreement between self-assessments and peer assessments, particularly at the upper levels (Excellent and Outstanding). This suggests a shared positive perception among evaluators regarding the traits being evaluated.

At elevated performance levels, most assessed characteristics exhibited a significant concentration in the notably Excellent and Outstanding categories, displaying exceptional performance across all evaluated domains. Functionality and visualization strategies (XR) emerged as the primary strengths, consistently receiving elevated-level appraisals. This assessment has permitted a comprehensive performance overview across diverse traits, identifying strengths and areas for further enhancement.

4.1.3. Identified Challenges and How to Overcome Them

While the students faced challenges in applying UX+XR, 75% of students overcame them through adaptation and using the provided tools. The difficulties were related to hardware problems and intricacies in the transformability and structural design workflow. These challenges helped them to grow and improve their design and problem-solving skills. To resolve the hardware challenges, we suggest preparing accessible computers for future studios for the students in the same XR lab. Regarding transformability and structural design, the team must include civil engineering and structural design experts for the entire design process.

During the observation and notebook analysis, we noticed that 10% of the students had challenges using specific VR platforms that did not provide student licenses. In this sense, we opened access to them to remotely connect to the laboratory computers and equipment with floating licenses in the school. We will only select the VR platforms that offer direct access to future design studios.

The UX+XR methodology has proven to be a valuable tool for transformable architecture design, providing a structured and user-centered approach. Students recognize its effectiveness in all project stages and highlight its contribution to academic and professional development. UX+XR methodology reflects a positive experience and significant support for integrating UX+XR into the educational curriculum, with 75% to 82% of students favoring its use across various evaluated areas.

4.2. Transcendence of the Methodology: UX+XR+AI+Inmotics

During our research, we have identified specific stages in the architectural design process that require special attention. We have addressed the following: (a) understanding the design process without hindering creative capacity; (b) grasping the data and the problem or need that must be addressed; (c) conceptualizing feasible, innovative solutions; (d) translating the conceptual and experimental phases to architectural development; (e) manage constant uncertainty and make flexible, assertive decisions responding to changes from professors, clients, and socio-economic contexts; (f) communicating ideas effectively between the student and the professor or client; and (g) materialize the tectonic idea to navigate the constructive process.

Preparing future architects and designers is a challenge that forces us to reflect on how ready our students are to be professionally competitive in the architecture and construction field. A common misconception is that using innovative digital technology will automatically lead to more innovative design. However, the focus should be on creating innovative design ideas and lasting values in human and urban memories, using technology as a platform for development. Design quality depends not on technology but on the brilliant mind behind it. Using digital tools as real-time spatial translators significantly enhances the perception and comprehension of design elements and values.

4.3. Transformable Architecture Final Projects

The aspects of AI and inmotics were expressed in interface diagrams that reflected the operativity, interactivity, and transformability of the designed transformable architecture.

During the studio, the transformability aspect responded to the design problem. It was based on design elements, focusing on understanding the difference between skeleton and skin as transformable agents. The students selected the materials and mechanisms based on the principles of transformation. Utilizing XR, the students simulated the transformation of the architecture installation. Grounded on UX+XR, the participants successfully designed an interactive sphere for stress management and memory stimulation in older adults, an interactive portal for parks, a transformable housing for people without homes, a transformable bus station, an educational pavilion to be assembled by children, and an installation to nurse babies in public spaces (see Figure 3). In this studio, the design scale was small to develop the AI interface and to dedicate attention to the construction details, joints, and assembly processes for the transformability of the space.

The design products proved high spatial quality and an understanding of scale and user-adapted design. The students showed prominent motivation and responsibility with the design, considering their commitment to the users. Including XR scenarios is needed to understand the proportions of the space and simulated movement, use, and transformability (see Figure 4).

Figure 3. Project products from the XR Assisted studio 2023: (a) Milkweed bench; (b) Transformable housing; (c) The Sigh; (d) The path of the sun; (e) Educational pavilion; (f) Bus station.

Figure 4. Project transformation process: (a) The Sigh; (b) The path of the sun.

5. Discussion of Results

The following discussion addresses three critical points identified during the study: (a) the enrichment of learning using digital technologies, (b) the development of structured and empathetic design processes through integrating UX and XR, and (c) the enhancement of spatial and perceptual learning through immersive XR environments.

Regarding enrichment learning through digital technologies, integrating digital technologies such as XR and AI in architectural design significantly impacts students' learning experiences. Including XR sparked students' curiosity and increased their participation in autonomous learning. Using immersive digital tools, students explored design concepts in ways that traditional methods did not allow; for example, in the conceptual exploration using VR, the students were able to sketch directly in VR, change the scale and level of detail for the conceptual sketches and create walkthrough in real scale. In the design development stage, the students could circulate their design with VR on a real scale, overlap it in the real site with AR, and create multiuser collaborative virtual reviews using MR and VR. The ability to interact with these technologies enables students to push the boundaries of conventional design methods, resulting in innovative solutions. Moreover, the independent use of these tools gave students greater confidence and a sense of ownership over their learning process.

As for structured and empathetic design processes, integrating UX principles with XR technologies provided an organized, phased approach to design, actively involving users throughout all process stages. This approach ensured that the designs not only addressed technical needs but also human expectations, effectively meeting the actual demands of the users. By focusing on real-world problems, students developed a more profound empathy toward users, seeing them as human beings with diverse needs and desires rather than just clients (Aguirre-Villalobos et al., 2024). This user-centered design approach promoted critical thinking, allowing students to identify potential challenges early in the design process, such as accessibility issues or visual scale problems. This method's collaborative and iterative nature helped connect the gap between theory and practice, giving students a more comprehensive understanding of design challenges (Ferrer-Mavárez et al., 2020).

Finally, XR technology enhances students' understanding of essential design elements, spatial relationships, light management, and spatialized sound for spatial and perceptual learning. The immersive environments provided by VR allowed students to perceive these elements in a much more intuitive and impactful way than traditional methods like models or renders. The ability to visualize and experience design concepts within immersive environments represented a significant advancement in the design process. This immersive interaction improved students' spatial and aesthetic understanding and helped them communicate their ideas more effectively (Rauschnabel et al., 2022).

XR offers unique opportunities to enhance spatial perception by creating synthetic environments that generate sensory responses. Integrating UX strategies into the teaching-learning process enabled dynamic actions such as exploring virtual spaces, interacting with design elements, and experiencing emotional reactions, enriching the students' design capabilities and allowing them to communicate their ideas more effectively.

We demonstrated that integrating XR and UX principles improved the transformable architectural design process by enabling a deeper understanding of spatial and sensory elements through immersive digital environment simulations. XR facilitated real-time visualization and interaction, allowing designers to successfully explore innovative solutions and address users' needs. Additionally, the structured and empathetic approach facilitated by UX ensured that designs were user-centered and responsive to human experiences, improving the quality of design outcomes. In the context of learning, these technologies optimized the teaching-learning environment by directly engaging students in the design process, fostering critical thinking, and encouraging autonomous learning. UX+XR contributed to a more dynamic, user-centered, interactive, and innovative design process by bridging the gap between concepts and practical applications.

In terms of reflections and recommendations, it is imperative to (a) consolidate strengths by persisting in reinforcing aspects with exemplary performance, functionality, and visualization strategies; (b) improve areas with lower evaluations by undertaking a comprehensive analysis of segments receiving lower ratings to pinpoint potential enhancements; and (c) evaluate continuously to ensure progress, sustain an ongoing assessment process, and adapt design and collaboration strategies based on findings.

Exploring XR for transformable and interactive design revealed several promising areas that warrant future investigation. This exploration highlighted the need to improve XR environments' UX. It focused on three fundamental areas: how immersive the experience is, how interactive it is, and how well it adapts to user needs. Examining how these technologies can affect education and other areas is important. We should explore how different fields can collaborate on XR projects. In essence, a comprehensive examination of the societal impacts of XR technologies is imperative and will be considered in future research.

6. Conclusion

Examining and assessing how UX and XR were applied in this research led us to the following significant findings.

Applying the UX+XR with AI/inmotics method gave students a unique opportunity to engage in innovative multidisciplinary projects. It allowed them to gain firsthand experience in designing and developing XR experiences, enriching their learning and preparing them to tackle the challenges of the constantly evolving workplace.

The UX methodology helped include users in all stages of the design process, ensuring that the design product and XR experiences were designed based on their needs, preferences, and abilities. This resulted in more intuitive, functional, and satisfying final products for the users.

User participation in the design process improved the quality of the XR experience and promoted a sense of belonging and community among users. By being considered and heard, users felt valued and were more likely to adopt and enjoy the XR experience.

Lastly, concerning the value of inter-university collaboration and multidisciplinary teams, the collaboration between three universities and the involvement of different experts and multidisciplinary teams in the project provided a broad and enriching perspective. The partnership allowed for addressing challenges from different angles and focalizing the knowledge and skills of each team member, resulting in more comprehensive and practical solutions.

Combining UX, XR, inmotics, and AI to design transformable and interactive experiences significantly benefited students and users. It fostered inclusion, participation, and interdisciplinary collaboration to create high-quality and relevant XR experiences.

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Conflict of Interests

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